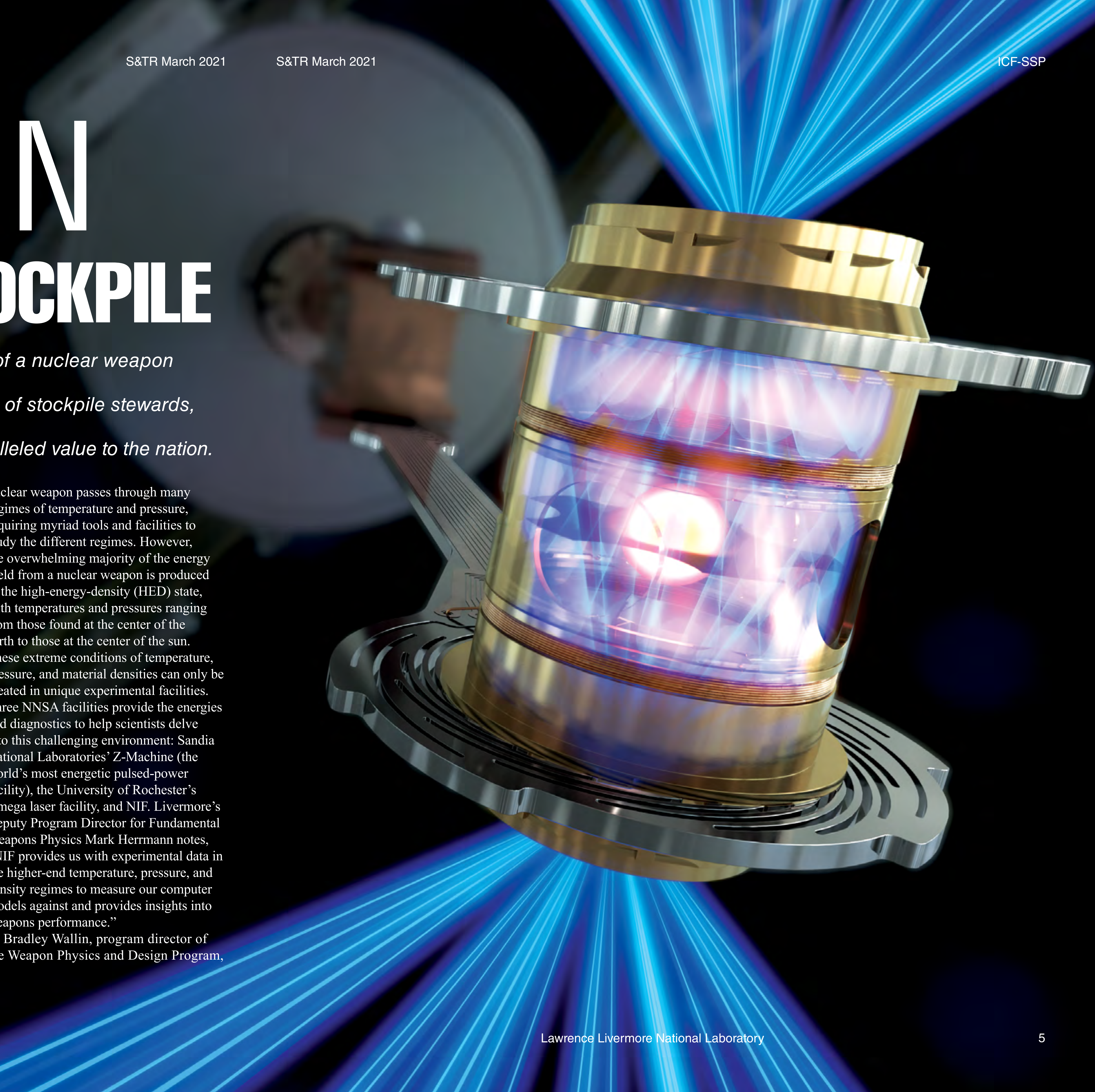
FUSION SUPPORTS THE STOCKPILE

From providing data that sheds light on the complex physics of a nuclear weapon to providing a valuable training ground for the next generation of stockpile stewards, Livermore's Inertial Confinement Fusion program brings unparalleled value to the nation.



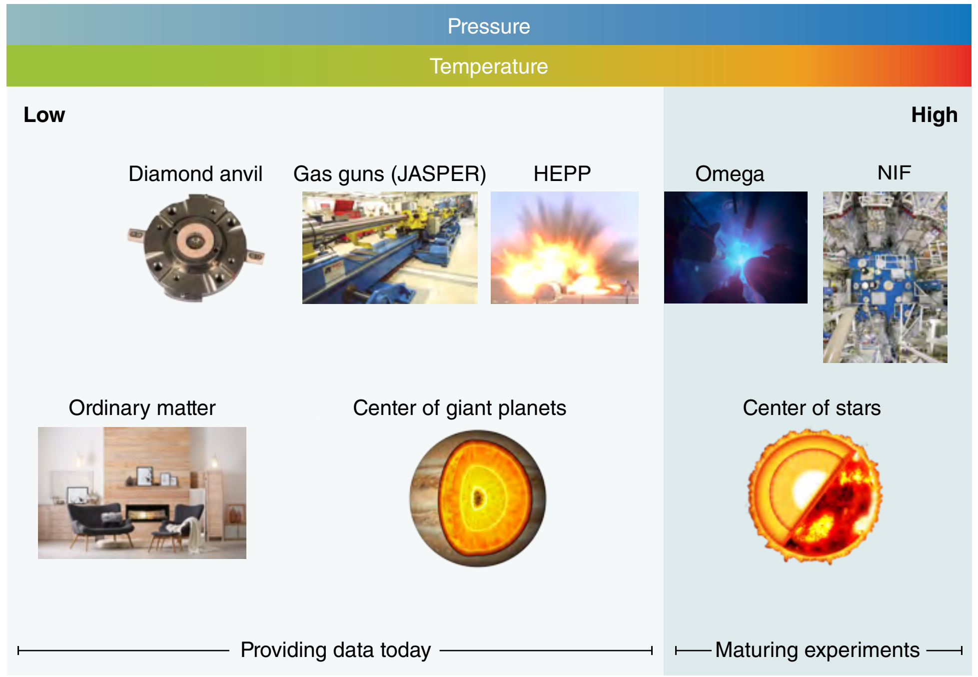
THE last U.S. underground nuclear explosive tests, which were key to assessing the design and viability of the country's nuclear weapons, occurred over 27 years ago. However, the need for deeper understanding of the complex physical processes that drive nuclear weapon performance and for putting stockpile design and assessment on a solid science-based foundation continue to be of utmost importance to the nation.

A core mission of the Department of Energy's (DOE's) National Nuclear Security Administration (NNSA) is to ensure this stockpile remains safe, secure, and reliable, without further underground testing. Lawrence Livermore's Inertial Confinement Fusion (ICF) program supports the Stockpile Stewardship Program (SSP) mission by seeking to recreate and examine the processes that occur in the heart of burning stars and nuclear weapons, through heating a tiny amount of encapsulated fusion fuel and compressing it to the point that nuclear fusion reactions occur. The data from experiments at ICF facilities help to refine computer models used to better understand and assess the performance of the stockpile's aging nuclear weapons. These experiments also provide an opportunity for weapon designers, experimentalists, engineers, and staff to tackle challenging design problems in the absence of underground nuclear explosive testing, thereby developing and refining the skills needed to support the SSP. This dedicated workforce turns to platforms of immense energy and engineering prowess, such as the world's largest and most energetic laser—the NNSA's 192-beam National Ignition Facility (NIF), located at Livermore—to meet the SSP mission, now and in the future.

Science Reveals the Stockpile

The end of underground testing and DOE's creation of the science-based SSP significantly increased the need to have a detailed scientific understanding of nuclear weapons and how they work (See p. 7: "The Quest for Fusion Ignition and the Birth of Science-based Stockpile Stewardship"). This requirement ushered in an era of large-scale experimental platforms and high-performance supercomputing facilities, paired with cutting-edge diagnostic capabilities. A detonating nuclear weapon passes through many regimes of temperature and pressure, requiring myriad tools and facilities to study the different regimes. However, the overwhelming majority of the energy yield from a nuclear weapon is produced in the high-energy-density (HED) state, with temperatures and pressures ranging from those found at the center of the earth to those at the center of the sun. These extreme conditions of temperature, pressure, and material densities can only be created in unique experimental facilities. Three NNSA facilities provide the energies and diagnostics to help scientists delve into this challenging environment: Sandia National Laboratories' Z-Machine (the world's most energetic pulsed-power facility), the University of Rochester's Omega laser facility, and NIF. Livermore's Deputy Program Director for Fundamental Weapons Physics Mark Herrmann notes, "NIF provides us with experimental data in the higher-end temperature, pressure, and density regimes to measure our computer models against and provides insights into weapons performance."

Bradley Wallin, program director of the Weapon Physics and Design Program,



Different tools are required for the various temperature–pressure regimes experienced by a nuclear weapon. Experiments at relatively low pressures and temperatures are conducted with diamond anvil cells (See *S&TR* July/August 2019, pp. 20–23). The conditions that reflect those at the centers of giant planets can be reproduced in gas-gun experiments in facilities such as the JASPER gas gun (See *S&TR* April/May 2013, pp. 20–23) and high explosive pulsed power (HEPP) experiments. Setting experiments at the fusion conditions created in stars and nuclear weapons requires facilities such as the pulsed-power Z machine, the Omega laser facility, and ultimately, the National Ignition Facility.

says, "As we reach into higher and higher areas of pressure, temperatures, and densities of materials in our experiments, we learn much along the way that is applied to many areas of stockpile stewardship." HED experiments and research provide data for design codes that aid in assessment of the stockpile. (See p. 11: "Simulations: A Powerful Tool in the SSP Toolbox.") For example, the combination of modeling and HED experiments helps researchers to better understand a weapon's survivability when facing possible hostile encounters in the stockpile-to-target sequence: the order of events involved in removing a nuclear weapon from storage and assembling, testing, transporting, and delivering it on the target. "The goal is to keep the nation's nuclear deterrent strong and viable," says Wallin. "A strong deterrent helps keep the peace." Additionally, some HED experiments at NIF focus on determining materials' equation of state (EOS)—the relationship between pressure, temperature, and density. Accurate EOSs for key elements are essential for generating the computational models that underpin simulations critical to SSP efforts such as life extension programs (LEPs), which aim to add 30 years of service life to aging nuclear warheads.

NIF is the only U.S. facility designed to perform experimental studies of fusion ignition and subsequent thermonuclear burn, the phenomenon that gives rise to the immense energy of modern nuclear weapons. For the ICF experiments at NIF, a capsule filled with deuterium–tritium (DT) fuel is seated inside a gold or depleted uranium hohlraum, which is a cylindrically shaped device with open ends. NIF's laser light enters through these open ends and strikes the hohlraum walls, generating a bath of x rays that causes the capsule to implode while heating and compressing the DT fuel into a central hot spot. Fusion reactions within the hotspot produce energetic alpha particles (also known as helium nuclei) and neutrons. The energetic alpha particles deposit their heat in the fusion fuel. For ignition to occur, enough heat must be deposited to generate a propagating burn wave from the hot spot into the cold fusion fuel. The yield of the fusion experiment can be measured by counting the number of neutrons generated.

NIF Director Doug Larson explains, "Achievement of ignition is critical since once the fusion fuel is ignited, higher fusion yields can be generated, opening a gateway to even higher energy densities that are needed for the SSP." In an experimental campaign that took place over several months in 2017 and 2018, scientists at NIF successively produced record numbers of fusion neutrons, culminating in a January 2018 shot that produced 1.95×10^{16} neutrons and 55 kilojoules, the highest yield to date (See *S&TR* April 2019, pp. 12–15). Recent results from a 2019–2020 campaign improved upon that, increasing the neutron yield by 4 percent at a much lower implosive velocity. LLNL's Chief Scientist for ICF Omar Hurricane explains, "The real significance of these results is that we can now drive the new target design to a higher implosion velocity using more laser energy, achieving greater fusion yield."

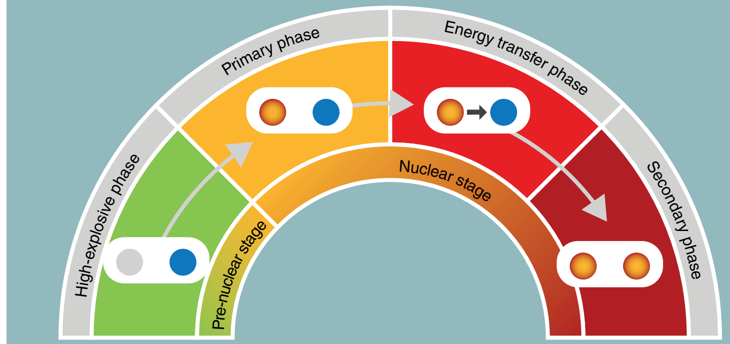
Addressing Ignition Challenges

Hurricane adds, "We've made incredible scientific progress over the past decade. Our understanding of the physics involved on the path to ignition increases with each step we take." Researchers have focused on such challenges as addressing hydrodynamic instability. "The first trick was to determine the one thing we could do that would make a significant improvement. The intuition and judgment of the weapon designer came into play as we evaluated different options. In this case, the 'fix' involved changing the shape of the NIF laser pulse, which improved the yield by a factor of 10." (See *S&TR*, June 2014, pp. 4–10). The resultant "high-foot" pulse, which lasts 15 nanoseconds and has three main shocks (instead of the 20-nanosecond pulse and four shocks used in low-foot shots), creates a stronger first shock in the foot, or early part, of the pulse. Experiments using this pulse shape proved more forgiving of imperfections in the fuel capsule and less susceptible to implosion instabilities that decrease fusion reactions.

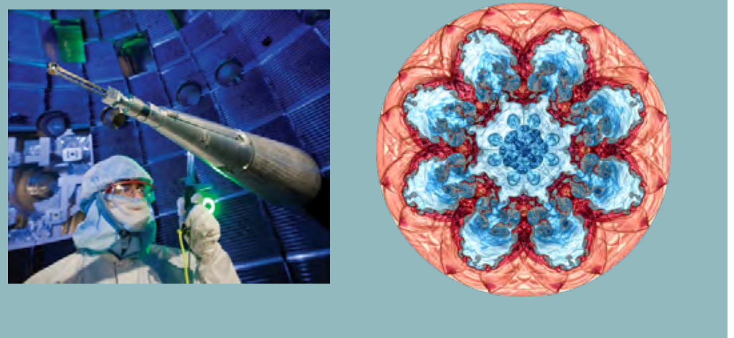
The Quest for Fusion Ignition and the Birth of Stockpile Stewardship

Soon after the invention of the laser in 1961, Livermore physicists John Nuckolls, Ray Kidder, and Stirling Colgate used Livermore-developed codes to study whether laser light might be able to trigger fusion reactions. Their results led to the launch of a small laser fusion project in 1971, which grew to develop a series of increasingly powerful lasers: Janus in 1975, Shiva in 1977, and Nova in 1984. The 1980s also saw the growing interplay between computer simulations and experiments, along with the birth of supercomputers.

Meanwhile, well before the 1992 underground nuclear test ban, DOE recognized that ICF could provide an alternative to underground tests for exploring radiation hydrodynamics—the study of the flow of matter that is strongly coupled with electromagnetic radiation, including x-ray radiation. Such radiation plays a critical role in the detonation of a nuclear weapon. After 1992, the question became, how would the nation maintain a deterrent in the absence of testing? Since modern thermonuclear weapons rely on fusion to perform, weapon researchers needed a platform upon which to explore fusion ignition and thermonuclear burn. Fusion in a weapon was one of its least-understood processes, so having the capability to reproduce this process in a laboratory setting has become one of the grand challenges for the science-based Stockpile Stewardship Program.



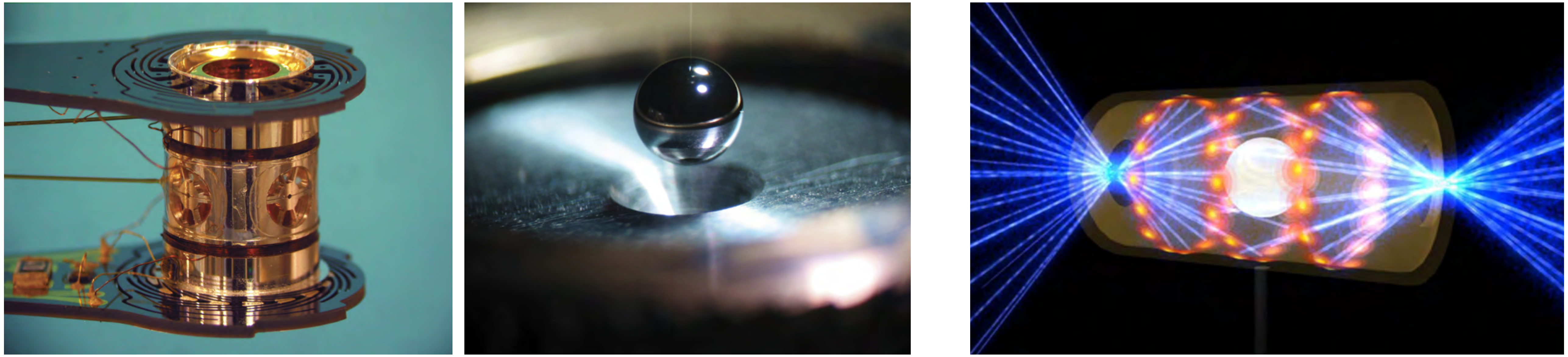
There are roughly four phases in a two-stage nuclear detonation. In the first "high-explosive" phase, high explosives compress special nuclear material, creating a supercritical assembly. The "primary phase" comes next, when the supercritical assembly fissions and initiates fusion reactions, ultimately creating a burst of neutrons and x-ray energy. Those x rays travel from the weapon primary to the secondary in the third "energy transfer" phase. Finally, the weapon secondary produces energy, explosion, and radiation in the "secondary phase."



Modern-day stockpile stewardship depends on experiments, historic test data, and high-performance computing to ensure the long-term viability of the U.S. deterrent without additional underground nuclear tests. Left: Before each NIF experiment, a technician uses a positioner to precisely center the target inside the chamber. The positioner serves as a reference to align the laser beams. Right: This simulation shows hydrodynamic instability of two fluids mixing in a spherical geometry. Such simulations provide valuable data sets for understanding turbulence models important to ICF and stockpile stewardship applications.

Once these hydrodynamic instabilities were removed, other issues emerged that had been masked by the larger problem. "It's like peeling away the layers of an onion," says Hurricane.

The next challenge to tackle was implosion asymmetry. Implosions act as amplifiers, taking 100 million atmospheres of pressure and increasing it to many hundreds of billions of atmospheres. Any asymmetries caused by, for instance, a tiny material defect in a capsule or a variance in



Left: Traditionally, fusion target capsules are about 2 millimeters in diameter and filled with cryogenic (super-cooled) fuel. Capsules are composed of plastic, diamond, or beryllium. Center: The capsule is held inside a hohlraum—a metallic case. Target handling systems precisely position the target and freeze it to cryogenic temperatures of 18 kelvins (-427 degrees Fahrenheit) to enhance the fusion reaction. Right: When NIF laser beams strike the internal walls of the hohlraum, they are converted to x rays that irradiate the capsule inside. The outer wall of the capsule rapidly ablates, or burns away, while the adjoining fuel layer implodes and compresses the capsule core.

one of the 192 laser pulses, gets amplified. “This is why we all work so hard to minimize any defects,” says Hurricane. For instance, the “tent,” or membrane that holds a capsule in place in the hohlraum, contributes to instability in implosions. This plastic support membrane, only 30–110 nanometers thick, touches the capsule along rings at the top and bottom of the capsules. Those tiny areas of contact are enough to perturb an implosion’s symmetry by perforating the ablator and shooting annular jets of material into the implosion (See *S&TR* March 2018, pp. 16–19; January/February 2016, pp. 4–11). Another feature that affects the implosion is the tube used to inject fuel into the capsule. “This tube, which is 1/10th the diameter of a human hair, was causing a jet of ablator material to shoot into the hot spot, cooling it down as we were trying to compress the capsule to heat the hot spot up,” says Hurricane. The target fabrication team at NIF shrank the tube to 2 micrometers in diameter, which reduced the jet, and are exploring whether a 1-micrometer fill tube might be feasible, if needed.

The work addressing these challenges and others continues. Notes Herrmann, “The data quality and diversity we now get from NIF is unprecedented and has given us a good idea of the limiters. We can’t quite compress the capsule as much as we need to, so we’re trying to figure that out, and also we are looking at how efficient we can make the hohlraum so we can drive bigger capsules that are more resistant to imperfections.”

In more recent ICF experiments, the research team fired a three-shock laser pulse (less than half the duration of pulses used in the high-foot campaign) lasting about 7 nanoseconds at the target. The precisely timed series of shocks propagated through the fuel capsule as it imploded. Some experiments adopted a strong initial shock, deemed the “big-foot” pulse, to drive a high-velocity implosion. A somewhat different strategy based on a more traditional pulse shape used a roughly 2-millimeter-diameter, high-density carbon (HDC) capsule that contained a thin layer of DT fuel located just inside the outer shell. HDC, or diamond, has a higher density than the plastic and beryllium shells previously used in ICF experiments and allows for a shorter pulse that still reaches the same kinetic energy. Recent record neutron yields have stemmed from the use of HDC capsules, a shortened laser pulse, a lower concentration of helium gas fill in the hohlraum, and a thinner fill tube, as well as enhanced understanding of the implosion process.

Scientists are also exploring different hohlraum shapes to increase the amount and symmetry of x-ray energy on the capsule, including a novel hohlraum shaped like a rugby ball (See *S&TR* July 2020, pp. 12–15).

Igniting a Passion for Stewardship

During the Cold War, underground nuclear testing at the Nevada Test Site was the centerpiece of the development and deployment of the U.S. nuclear stockpile. The tests were “final exams,” not only for the nuclear warheads themselves but for the laboratory scientists and engineers, who were continually experimenting with new ideas, apparatuses, and diagnostics.

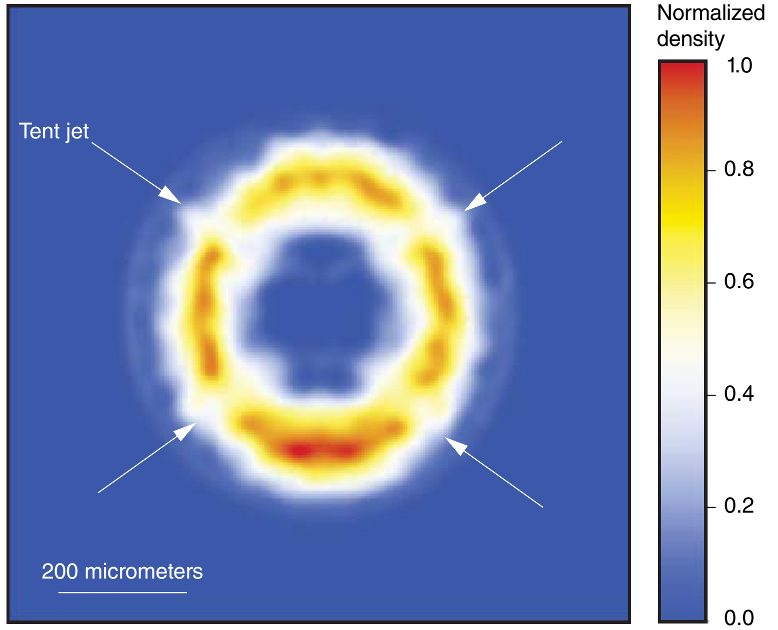
With underground testing now in the past, the venue has changed, but the challenges remain. Debbie Callahan, deputy for integrated experiments and associate division leader for HED-ICF in design physics, explains that the ICF experiments conducted today at NIF and elsewhere serve as the same training ground for today’s researchers. “We are training the designers and experimentalists to make decisions and hone their intuition.”

Just as with the underground experiments of decades before, ICF experiments are complex, requiring much time and coordination. Designers and experimentalists work in tandem on an ICF experiment that can take a year or more from concept to the final shot. Designers use codes and theories to develop an experimental design that will address a particular challenge; experimentalists determine the diagnostics that will best capture the test results and analyze the data. But the lines of responsibility are often blurred, with experimentalists and designers working together to address the challenge.

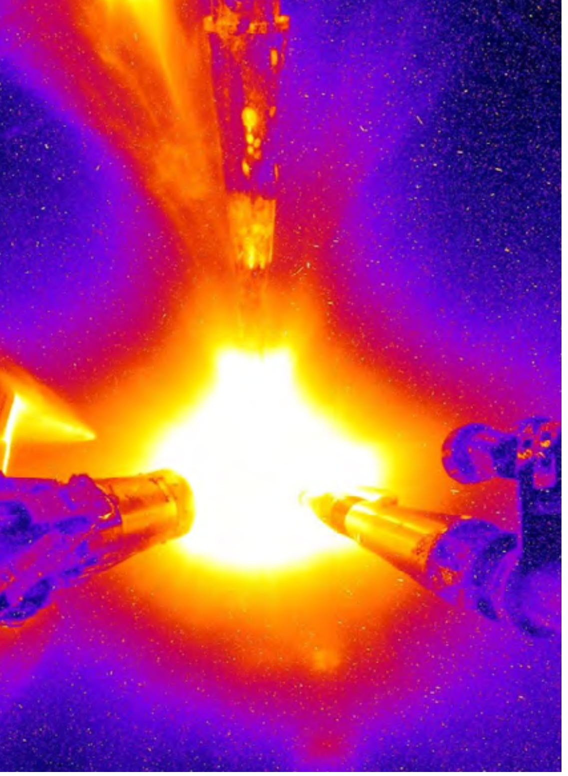
A case in point is designer Andrea Kritcher and experimentalist Dan Casey. Kritcher, a designer in the ICF program, came to the Laboratory in 2009 as a Lawrence Fellow. In one of her projects, she used x-ray Thomson scattering to characterize fusion targets for ignition experiments at NIF, diagnosing the compression-phase temperature and density conditions of the implosion capsules. (See *S&TR* June 2011, pp. 4–12.) Casey arrived at LLNL in 2012 and became lead experimentalist for several NIF and OMEGA campaigns supporting NNSA programs, including the Big Foot campaign. Two and a half years ago, Kritcher and Casey teamed up as lead designer and lead experimentalist for the ICF program’s Hybrid-B campaign. Now completed, this campaign was one of several focused on taking the best elements of past designs and using data-based understanding of the key physics factors that control symmetry and performance. The goal of such “hybrid” implosion design work is to field large-scale, ignition-relevant implosions using NIF’s full power and energy capacity.

The Hybrid-B campaign sought to determine how big a capsule would fit in a traditional hohlraum and how it could be driven to relevant velocities.

“Ultimately, we wanted to determine if we could field bigger implosions using our existing hohlraums by optimizing several design parameters including the size of the capsule compared to the size of the hohlraum,” says Kritcher. Casey adds, “There was a lot of effort involved, from developing the initial design, to the design and building of the target, preparing the diagnostics, conducting preliminary ‘tuning’ shots that help us better grasp the



The “tent” that holds the hohlraum capsule in place affects the quality of the implosion. Where the capsule touches its “tent” in a ring shape, as depicted in this x-ray snapshot of the imploding capsule, the points of contact cause upper and lower ring jets to penetrate the shell as it implodes and quench the yield of inertial confinement fusion experiments.



In February 2016, the ICF program conducted its first layered deuterium-tritium (DT) fusion implosion using the “big-foot” three-shock pulse with a sub-scale diamond ablator and a thinner DT ice layer, and a low-gas fill to limit laser–plasma instability and cross-beam energy transfer. Credit: Don Jedlovec.

implosion shape, shock trajectories, and so on, before we can conduct the final, integrated shots.” The Hybrid-B campaign included seven tuning experiments and six final integrated experiments using three different case-to-capsule ratios, including a capsule with the largest radius fielded to date: 1.2 millimeters.

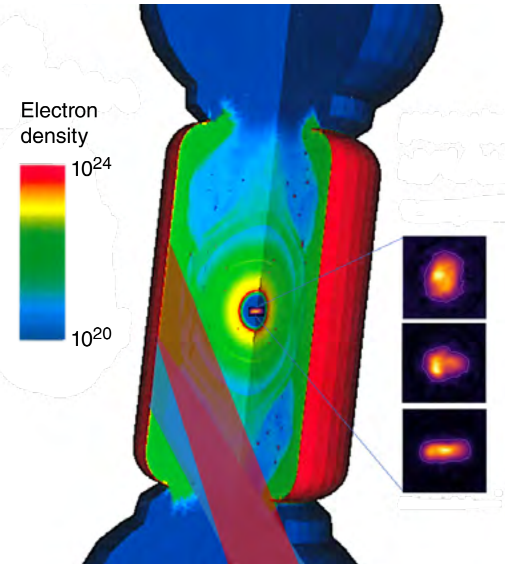
For the lead designer and experimentalist, the day when a full integrated NIF test shot is to occur is imbued with much of the same anticipation and tension that was present in the legacy underground test shots. “Final tests are both exciting and gut-wrenching,” says Casey. “It’s the moment of truth.” A year or two of effort has gone into the design. An enormous number of instruments, sensors, control systems, and diagnostics are involved, as well as hundreds or thousands of person-hours. Right before the shot, sirens and alarms sound for clearing the NIF target bay. The physicists stand by in the control room, waiting. From the control room, the shot is heard as a faint “pop.” “Ten, fifteen minutes go by before you know what has happened,” says Casey. “You keep hitting ‘refresh’ on the data download.” The data trickles in over the next few days, so it takes a while for the final results to arrive. Kritcher adds, “We always look forward to the data that tells us the quality of the implosion—particularly how symmetric it was—and how well the results match the predictions. And we are always eager to see the results of the many nuclear diagnostics that provide a wealth of information about how well the fuel came together at the end of the implosion, although the first question we usually get asked is ‘what was the yield?’!”

The shot’s neutron yield is determined from data gathered from a variety of diagnostic instruments, including the neutron time-of-flight (nTOF) detector, which records the neutron energy spectrum; fuel temperature; bang time (the time of peak neutron emission); and areal density, which is a measure of the combined thickness and density of the imploding frozen fuel shell. For ignition to occur, the fusion fuel must have a high enough areal density and temperature, as well as a symmetric shape at the time of peak compression (See *S&TR* December 2012, pp. 15-17).

Kritcher notes that working on ICF on NIF is a major part of the excitement of working at the Laboratory. “It’s a unique opportunity to work hands-on in an experimental campaign, solve problems in real time, and engage in real-time decision-making. There are the models, and there are the experiments… they don’t always agree, and testing gives us a chance to hone our intuition and learn why our models don’t always agree with the experiments. We can set the models to reflect results obtained in past shots, but once you change the designs, you often need the data from new experiments so you can incorporate new features in the models.”

Of course, the lead designer and experimentalist in a campaign are not working alone. There are 15 to 20 physicists who take on various roles in a campaign, split between designers and experimentalists. To bring an experiment to fruition requires an army of others who have responsibilities in the facility, in building and assembling the required targets, and in setting up the experiments.

With Hybrid-B behind them, Kritcher and Casey are involved in testing a different target design. “Experimentally, we’re still not getting the areal densities we want,” says Kritcher. “So, for this campaign, the capsule will have a thicker DT ice layer, which should increase the areal density and be less susceptible to capsule imperfections. To drive the thicker ice layers to relevant implosion velocities, we will use high-temperature hohlraums.” The initial design phase and reviews are complete; experiments began in summer 2020 and extend into fiscal year 2021.



Left: A simulation of electron density during implosion of a target for the Hybrid-B campaign, created by LLNL’s HYDRA radiation hydrodynamics code. ICF design physicists use HYDRA to simulate the entire ignition target in 3D, including the hohlraum and capsule. Areas of higher electron density correlate to areas of higher-density plasmas. Right: The measured hot spot x-ray emissions of three different shots using capsules of different diameters, captured by x-ray penumbral imaging, showed the impact of case-to-capsule ratio on hot-spot symmetry.

Simulations: A Powerful Tool in the SSP Toolbox

Along with experiments and legacy data, stockpile stewardship requires advanced supercomputer facilities that can conduct simulations at scales of interest. As LLNL retiree Dick Fortner, a former associate director during the underground testing era, explains, “Even during the test era, physical experiments and computer modeling went hand in hand, and the results balanced and reinforced each other. Experimental data was needed to do the calculations. And you get the calculations to see if you understand the data. It’s still true today, as we continue to test the codes and models. If the results or predictions from the models doesn’t fit the experimental data, then you have to fix the models.”

The Sierra supercomputer is the latest in a series of NNSA’s leading-edge Advanced Simulation and Computing (ASC) program supercomputers, whose predecessors include Sequoia, BlueGene/L, Purple, White, and Blue Pacific. Sierra is helping to solve the most demanding computational challenges faced by the ASC program in furthering its stockpile stewardship mission (See *S&TR* August 2020, pp. 12–15). At peak speeds of up to 150 petaflops (a petaflop is 10^{15} floating-point operations per second), Sierra provides at least four times the performance of Sequoia.

Data analysis is also benefitting from the explosion in computing power that comes with bigger, faster machines, such as Sierra and the Trinity supercomputer at Los Alamos National Laboratory. Machine learning (ML) uses computers to learn from data and make predictions about the environment (See *S&TR* March 2019, pp. 4–11). For example, one project leveraged ML to analyze the largest-ever data set from ICF implosions on NIF, pointing the way toward new laser target designs (See *S&TR* September 2018, pp. 16–19). Another group is developing an innovative cognitive computing platform that combines ML with graph analytics and other areas of artificial intelligence to improve ICF simulation efficiency.

From past to present, Livermore has employed the most powerful computer systems available to support stockpile stewardship design and test efforts. Left: The Univac, Livermore’s first supercomputer, had 5,600 vacuum tubes, a 6-kilobyte memory, and a code stored on magnetic tape. Right: LLNL’s newest supercomputer system, Sierra.

The Future Beckons

As Callahan notes, when it comes to training the next generation, it’s a journey. “We are training people to be the future leaders and stewards for a stockpile that must stay viable for the next 30 years,” she says. “We are training them to develop good judgment and intuition, so whether they are designers or experimentalists, they can apply their knowledge on the very difficult problem of inertial fusion for a better understanding of the behavior of the stockpile in these very high-energy regimes.” Through experiments and simulations, the understanding improves. Experimental data informs new codes, adding and validating the models that underpin the simulations. Conversely, the models inform the experiments, providing guidance for what to expect, tools for pushing the limits of the known.

“The end goal of the ICF mission is to create the high yields that are the gateway to the high energy densities in nuclear weapons in which the stockpile stewards of the future can test their ideas under conditions that closely approach those of operating nuclear weapons. As to the first step of ignition, we’ve come a huge distance over the past decade in our understanding and capabilities,” says Herrmann. “There are certainly challenges remaining, and we can’t say for sure we will get there. Some of the issues we think we know how to fix. Others, we need to get a better understanding.” He points out that 10 years ago, the energy required to reach ignition was more than a factor of 10 away. He adds, “Now it’s about a factor of two or three, and we’re working on how to close the remaining gap.”

—Ann Parker

Key Words: Advanced Simulation and Computing (ASC) Program, big-foot, deuterium-tritium (DT) fuel, fusion ignition, high-density carbon (HDC), high-energy density (HED), high-foot, hohlraum, Hybrid-B campaign, HYDRA, implosion asymmetry, inertial confinement fusion (ICF), life-extension program (LEP), National Ignition Facility (NIF), nuclear deterrent, nuclear weapons, plasma instability, Sierra supercomputer, Stockpile Stewardship Program (SSP), target, underground nuclear test.

For further information, contact Mark Herrmann at (925) 423-5719 or herrmann9@llnl.gov.